N91-21596

SECTION VII.

REPORT OF THE PANEL ON EARTH ROTATION AND REFERENCE FRAMES

CONTRIBUTORS

Jean O. Dickey
Steven R. Dickman
Marshall T. Eubanks
Martine Feissel
Thomas A. Herring
Ivan I. Mueller
Richard D. Rosen
Robert E. Schutz
John M. Wahr
Charles R. Wilson

SECTION VII.

TABLE OF CONTENTS

1. SUMMARY

Introduction

Earth rotation studies (encompassing precession, nutation, polar motion, Universal Time, and the length of day) are significant because Earth rotation variations provide a unique and truly global measure of natural and man-made changes in the atmosphere, oceans, and interior of the Earth. These studies require the combined efforts of all the Earth science disciplines, and thus enforce a global perspective upon those disciplines and promote mutual interaction. Earth rotational dynamics depend upon the physical properties, structure, and processes within the Earth and contribute to all the disciplines concerned with these properties and processes. The Earth's rotation varies on time scales from minutes to millions of years, allowing Earth rotation studies to link related processes occurring over vastly different time scales, such as earthquakes with continental drift, weather with long term climate change, and water supply with glacial cycles. Finally, monitoring the rotational variations of the Earth is needed to properly determine the reference frames which are required for all studies concerned with motion of the crust and interior of the Earth. The enhancement and realizations of the reference frames and their connection are of key importance and are required for the proposed FLINN network

Current Status

Space geodetic techniques, including laser ranging to the moon and artificial satellites (LLR and SLR) and very long baseline interferometry (VLBI) using radio telescopes, have brought about a new age in Earth rotation and related studies. The length of day and polar motion are now routinely determined at the one to two milliarcsecond level, representing a ten-fold improvement in accuracy relative to traditional techniques based on optical astrometry. Periodic corrections to the standard nutation model have been determined to 0.1 milliarcsecond for many terms. These unprecedented accuracies, in combination with complementary geophysical observations of the atmosphere, oceans, seismic waves, and the magnetic field, have provided insights into the most fundamental properties of the Earth and their changes in time, such as: the measurement of changes in the Earth's equatorial bulge; bounds on the size of irregularities in the shape of the core-mantle boundary; landmark measurements of the rate at which lunar tides are slowing the Earth's rotation; detection of short-term variations in polar motion associated with atmospheric pressure variations; and understanding of the zonal angular momentum balance of the atmosphere as manifested in length-of-day changes over time scales from days to several years. In addition, the reference frames defined by SLR, LLR, and VLBI now agree to within a few centimeters as a result of common-site occupations by the various space-geodetic techniques.

Objectives for the Next Decade

The scientific objectives of Earth rotation studies for the next decade are as follows:

Observe and understand interactions of air and water (oceans, groundwater, and ice) with the rotational dynamics of the Earth, and their contributions to the excitation of Earth rotation variations, over time scales of hours to centuries;

Observe and understand the effects of the Earth's crust and mantle on the dynamics and excitation of Earth rotation variations over time scales of hours to centuries;

Observe and understand the effects of the Earth's core on the rotational dynamics of the Earth and excitation of Earth rotation variations over time scales of a year and longer;

Establish, refine, and maintain terrestrial and celestial reference frames.

Careful reference frame definition, refinement, and maintenance are of great importance in cartography and space navigation, and are essential to the six scientific objectives of the Solid Earth Sciences Program. For example, the terrestrial reference frame, which is determined in the course of Earth Rotation determinations and is linked to the extragalactic reference frame as well as to the center of the Earth, will be the best candidate to provide the primary reference frame to the FLINN network. In addition, observation and analysis of high precision Earth rotation variations will contribute to each of these six as follows:

Objective 1:

Earth rotation observations provide a unique way to study physical properties of and motions within the inaccessible core and to constrain magnitudes of viscous, magnetic and pressure forces acting at the core-mantle boundary.

Objective 2:

Earth rotation observations provide the basis for an absolute reference frame for the description of plate motion and associated mantle convection.

Objective 3:

Earth rotation variations arising from tectonic activity constrain the rheology of the lithosphere, and secular rotational variations may provide global constraints on other sources of mass redistribution such as sedimentation and erosion.

Objective 4:

High precision Earth rotation observations will provide integral measures of deformation, and its time history, associated with earthquakes and tectonic processes.

Objective 5:

Secular Earth rotation variations constrain the history of the glacial ice masses over the Pleistocene.

Objective 6:

Earth rotation observations provide integral measures of changes over the globe in the distribution and motion of air and water due to both natural and man-made causes. These observations also provide integral measures over the globe of the forces between the earth and its fluid envelope.

Requirements

To accomplish the Scientific Objectives, the following programs are required:

1. Improvements in observations and analysis

   Determine the rotation vector and its variations with the highest possible accuracy (at least 0.1 milliarcsecond) and with a sampling frequency of at least four cycles per day.

Improve analysis and modelling capabilities to a level commensurate with the improved spatial and temporal resolutions.

Collect improved ancillary data from geophysical, oceanographic, and atmospheric sources to enhance the interpretation and understanding of fundamental processes.

Pursue alternative synergistic and innovative approaches for Earth rotation measurements, such as the emerging global network of GPS stations and other new techniques.

2. Improvements in celestial and terrestrial reference frames and reference frame connections.

To monitor and refine the celestial and terrestrial reference frames needed for Earth rotation and crustal motion studies, as well as space exploration, the following actions are required:

Extend the quasar source catalogues to include additional suitable sources primarily in the Southern Hemisphere and along the galactic equator.

Expand the quantity, quality, and global distribution of LLR observations to allow the continuing and accurate determination of the dynamical reference frames, the Lunar/ Planetary Ephemerides.

Enhance and monitor the origin, orientation, and scale of the terrestrial reference frames and their ties at the 1 millimeter level, using techniques such as SLR.

Tie the above reference frames together and to those defined by artificial satellites using techniques such as colocation or differential VLBI.

In coordination with other US agencies and other nations, establish a minimum of three space-geodetic observatories per major tectonic plate, at sites distant from the plate boundaries, with regular measurement programs to monitor intraplate stability.

Establish a program of regular auxiliary measurements, such as gravity, at key globally distributed sites.

3. Improved observations of crustal motion and mass redistribution on the Earth

To permit quantitative comparisons between Earth rotation variations and crustal deformation, millimeter-level geodetic positioning is required at selected locations, over distances of 100 km or larger, on time scales of days (for co-seismic deformation) to decades (for post-glacial rebound).

Quantitative comparisons between changes in Earth rotation and oceanic mass will require determinations of global sea level.

Such quantitative studies will also require suitable monitoring of temporal variations in the gravity field.

2. FOREWORD

The Earth is an interacting system with separate parts: the solid Earth, the atmosphere, the oceans, the liquid core and the solid inner core. These systems exchange energy and angular momentum among themselves, through a rich variety of geophysical processes, and studies of the motion of the Earth as a whole, as well as its parts, shed light on these processes, as well as on the properties of the Earth. Earth rotation variations provide a unique and truly global measure of natural and man-made changes in the atmosphere, oceans, crust, and interior of the Earth. Because Earth rotation studies require the combined efforts of all the Earth science disciplines, they enforce a global perspective upon those disciplines and promote mutual interaction. Earth rotational dynamics depend upon the physical properties and structure of the Earth and contribute to all the disciplines concerned with these properties. Because the Earth's rotation varies on time scales from minutes to millions of years, Earth rotation studies link related processes occurring over vastly different time scales, such as earthquakes with continental drift, weather with long-term climate change, and water supply with glacial cycles. Finally, monitoring the rotational variations of the Earth is fundamental to the definition of reference frames which are required for all studies concerned with motion of the crust and interior of the Earth.

The topics considered by the Earth Rotation and Reference Frame Panel fall into several categories: (1) the orientation of the solid Earth about its axis of spin (or its time derivative, the length of day or LOD); (2) polar motion, i.e., the motion of the rotational axis with respect to the solid Earth; (3) nutation and precession, the motion of the rotation axis of the solid Earth with respect to inertial space; (4) terrestrial and celestial reference frames, i.e. the coordinate systems to which the above determinations are referred. Temporal variations in the Earth's mass distribution and its geopotential as well as Earth tides will be addressed, as these phenomena affect the above enumerated topics, but they will not be covered in full depth. It is assumed that a complete treatment will be given by another panel. The topics described here are by their very nature interdisciplinary, drawing from and contributing to the fields of geodynamics, seismology, meteorology, oceanography, hydrology, astronomy and celestial mechanics. As such, we will be interacting with several panels including Earth Structure and Dynamics, Geopotential Fields, and Measurement Techniques. The panel has used the results of the Workshop, "Interdisciplinary Role of Space Geodesy" as a starting point; we refer the reader to Chapters 2 and 7 of the Workshop Proceedings (I.I. Mueller and S. Zerbini, editors; published in Lecture Notes in Earth Sciences Series; Springer-Verlag, New York, 1989) for a complete discussion of these topics and for references.

3. CURRENT STATUS

3.1 Introduction

Earth studies have embarked on a new era with the advent of highly accurate space geodetic techniques and the availability of complementary geophysical and meteorological data sets. Universal time and polar motion are routinely determined at the one to two milliarcsecond level of accuracy (one milliarcsecond corresponds to 3 cm on the surface of the Earth or to 0.07 milliseconds in time), with higher accuracy being achieved in some cases. Periodic corrections to the standard nutation model have been determined to 0.1 milliarcsecond for many terms. These technological advances have led to the detection and analysis of geophysically interesting variations in all areas of Earth dynamics. Several examples include: the detection and measurement of changes in the equatorial bulge (J_2) of the Earth, inferences concerning the core-mantle boundary topography, new landmark estimates of tidal energy dissipation in the Earth-Moon system, detection of short-term variations in polar motion and their association with atmospheric pressure variation, and analysis of intraseasonal oscillations in atmospheric momentum which cause observable changes in LOD.

The high accuracy of the space geodetic techniques and the analysis of the resulting data sets have stimulated new and important theoretical developments which will prove crucial to the interpretation of the data and to the understanding of the phenomena brought to light. Examples of such theoretical progress include the prediction of nutation and wobble based on fairly realistic Earth models, accurate description of global ocean tides (semi-diurnal, diurnal, and long-period), quantification of mantle anelastic effects on rotation, and modelling of the viscoelastic deformation of a stratified Earth.

3.2 Current Observations and Measurements

The modern measurement types include lunar laser ranging (LLR), satellite laser ranging (SLR) and very long baseline radio interferometry (VLBI). In each technique, changes in Earth orientation are monitored by observing extraterrestrial objects from the surface of the Earth. The observed objects are used to approximate a nonrotating reference frame, either directly in the case of slow moving objects, or from dynamical theories of their motion, in the case of planetary and satellite observations. In each case, Earth orientation is estimated from the apparent motion of the Earth with respect to this frame. The measurement types and programs are summarized briefly below.

<u>Lunar Laser Ranging.</u> Lunar laser ranging (LLR) data consist of estimates of the round-trip time of flight of laser pulses from terrestrial observatories to retroreflectors placed on the Moon's surface by the Apollo astronauts and by unmanned probes from the Soviet Union. Lunar laser ranging can provide the monitoring of Universal Time with a temporal resolution shorter than a day. The ability to model accurately the lunar orbit since the first observations in 1969 allows the determination of the Earth's nutations and long-term studies of variations in Universal Time, as well as the determination of many parameters of the Earth-Moon system. One asset of LLR is its ability to provide rapid determinations of the Earth's rotation; literally a determination can be made as the Moon sets. The current network consists of three observatories: McDonald Observatory (Texas), another atop Mt. Haleakala (Maui), and the third in southern France near Grasse.

<u>Satellite Laser Ranging (SLR).</u> In this technique, very short laser-generated pulses of light are transmitted to retroreflectors mounted on the surface of artificial satellites; the round-trip travel times of these pulses (and hence the path lengths) are measured. A series of SLR measurements from a global network of about twenty stations permits the determination of orbital parameters, a

satellite ephemeris and relative station locations. High-quality Earth rotation data, as well as other quantities of geophysical interest (e.g., plate motion and gravity field studies), are generated by SLR. The best geodetic data come from laser ranging to the LAGEOS (Laser Geodynamics Satellite) target, a dense sphere placed in a high (6000 km) orbit. The orbit of this satellite can be used as a nonrotating reference system only for periods short compared to a year. Because polar motion induces a diurnal residual motion of an observatory (as seen from a nearly inertial reference frame), the stability of the LAGEOS orbit is sufficient to provide highly accurate and stable polar motion estimates, while LAGEOS UT1 estimates diverge from the true UT1 after a few months. The LAGEOS data are used, however, in studies of high-frequency changes in the UT1 or LOD. LAGEOS determination of polar motion and Earth rotation rate variations are made every three days.

Very Long Baseline Interferometry (VLBI). Radio interferometry is currently used to make highly accurate measurements of UT1 (the orientation of the Earth's rotation axis in space (nutation and precession), and polar motion with observing times of from a few hours to a day. The VLBI measures the interferometric group delay, the difference in the time of arrival of a radio signal at two or more radio telescopes. The delay rate (the time derivative of the interferometric phase delay) is generally measured as well. The interferometric delay between two telescopes is a direct estimate of the projection of the baseline vector (the vector between the telescopes) in the direction of the radio source. Observations from one baseline are thus not sensitive to rotation about that baseline. For single-baseline results (two stations), two components of Earth orientation are determined: local universal time, UT0 and the variation of latitude. Multibaseline VLBI can measure all three components of the Earth orientation if some of the baselines are nonparallel. Regular independent VLBI estimates of the Earth orientation are now produced routinely every five days with UT0 determined daily

International Cooperation. The above-described programs are coordinated under the auspices of the IAU/IUGG International Earth Rotation Service (IERS), for a unified determination of the Earth's orientation and the maintenance of celestial and terrestrial reference frames. The most recent (1989) realization of the IERS Celestial Reference Frame includes 268 radio sources, which would include only 41 without the NASA contribution. The IERS Terrestrial Reference Frame is based on 20 colocation sites, which would be 13 without the NASA only sites; similarly, the total number of sites in the reference frame would drop by about 25% without NASA.

3.3 Reference Frames

Solid Earth science has become the subject of intensive research during the last decades, involving plate tectonics, on both the intraplate and interplate scale, i.e., the study of crustal movements and of mantle connection, and the study of Earth rotation and of other dynamic phenomena such as the tides. Related efforts are directed towards improving our knowledge of the gravity and magnetic fields of the Earth and of the Earth's internal structure. A common requirement for all these investigations is the necessity of a well-defined coordinate system (or systems) to which all relevant observations can be referred and in which theories or models for the dynamic behavior of the Earth can be formulated. In addition, reference frames are of great importance in navigation and cartography. In view of the unprecedented progress in the ability of geodetic observational systems, as well as in the theory and model development, there is a great need for the definition, practical realization, and international acceptance of suitable coordinate system(s) to facilitate such work. The reference frames of VLBI, LLR and SLR are an inherent part of the above applications. Naturally, the goal is to have the frames themselves determined well above the measurement accuracy in order to optimize and combine the information content from the various complementary techniques. In general, each space geodetic system defines a reference frame based on technique-dependent considerations. Furthermore, each technique makes some unique contribution to reference frame considerations. For example, the VLBI technique provides a direct link to the already adopted celestial reference frame, but it has no sensitivity to the Earth's center of mass and measures baselines. Conversely, SLR is sensitive to the center of mass but is nearly independent of the adopted celestial reference frame. LLR is sensitive to the center of mass, defines its own celestial reference frame, the lunar ephemeris, which is a component of the planetary ephemerides, is of great importance in space navigation and in the unification of reference systems.

Contemporary geodesy has led to the development of two principal celestial coordinate systems: the planetary/lunar ephemeris frame based on the major celestial bodies of the solar system; and the extragalactic frame constructed from observations of quasars. It should be noted that both the extragalactic and ephemeris frames generate complementary terrestrial frames as well. Other celestial and terrestrial frames are developed through the analysis of the data from Earth-orbiting satellites [e.g. GPS (Global Positioning System), Doppler, laser reflecting satellites such as LAGEOS or ETALON]. The celestial and terrestrial coordinate systems from a single technique and class of target are related through adopted parameters, which are determined and published by the IERS. Each frame is rotated and translated with respect to the others; these offsets may be time variable.

Measurements are inherently more accurate in their "natural" frame and hence should always be reported as such. However, to benefit from the complementarity of the various techniques, knowledge of the frame interconnections (the rotation translation and the time-variable offset) is essential. The lunar/planetary system, integrated in a joint ephemeris, is by its nature unified by the dynamics. The radio frame is tied to the ephemeris frame in several ways; one is via differential VLBI measurements of planet-orbiting spacecraft and angularly nearby quasars. Another is the determination of a pulsar's position in the ephemeris frame (via timing measurements) and the radio frame (via radio interferometry). Very Large Array (VLA) observations of the outer planets (Jupiter, Saturn, Uranus and Neptune) or their satellites provide an additional tie between these two frames. At the present time, the links between VLBI, LLR and SLR have been obtained through the use of colocated systems using both fixed and mobile instruments. Although a few sites exist where more than one space geodetic technique is used in a permanent mode of operation, most ties between systems have been determined with mobile occupations of the same or a nearby geodetic mark. In such applications, the accuracy of local survey ties is of critical importance. In 1989, comparisons between VLBI and SLR using more than ten sites at which the local survey ties were known resulted in RMS differences of 2-3 cm after application of determined translation, rotation and scale parameters. This agreement is near the internal system accuracy of the respective techniques.

3.4 Variations in the Length-of-Day

The exchange of angular momentum between the atmosphere and solid Earth is evident in fluctuations in the length-of-day (LOD) at periods of a year and less. Recent improvements in Earth rotation measurements have been accompanied by improvements in numerical models and measurements of Earth's global atmosphere which can be used to calculate the atmospheric angular momentum (AAM). Both U.S. and foreign meteorological services maintain global atmospheric models for weather forecasting; surface and upper-air wind data and other meteorological measurements are assimilated into these models on a regular basis. Certain atmospheric variables, including pressure and horizontal wind velocity, are estimated at each model grid point at twelve-hour intervals by combining measurements of these variables with their forecasted values in a statistically optimal fashion. Calculation of an effective atmospheric excitation function, c, a three-dimensional pseudo-vector including Love number corrections for rotational and surface loading deformation of the Earth, can be made directly from the meteorological data. From intercomparisons between fluctuations in c_3 (the axial component of c) and in LOD, it has been established that non-tidal rotation rate variations over time scales less than about two years are largely due to atmospheric effects. There is a dominant seasonal cycle and additional variability on the intraseasonal (30 to 60 day) and interannual time scales. The correlation between LOD and AAM is so well established that numerical forecasts of atmospheric angular momentum are now being considered for the purpose of predicting Earth rotation variations. There are also short-period fluctuations in the LOD due to solid Earth and ocean tides which arise because of tidal perturbations in the Earth's inertia tensor. The largest tidally induced LOD fluctuations occur for the fortnightly, monthly, semi-annual, and annual tides. The amplitudes of these oscillations are sensitive to mantle anelasticity, which is not well constrained in this frequency range.

On interannual time scales, LOD changes appear to be related to atmospheric and climatic phenomena such as the quasi-biennial oscillation and the El Niño / Southern Oscillation. However, at periods of more than several years, the "decade" fluctuations remaining in the LOD series are so large (maximum amplitude ≈ 5 msec) in amplitude that they cannot be atmospheric in origin. Their most likely cause is torques exerted by the core on the overlying mantle. In addition, the effects of long-period variability in the global ice and water budget may affect the rotation rate over several decades.

Because we have no direct access to the core, Earth rotation observations are of prime importance in the study of the structure and dynamics of the Earth's deep interior. In general, torques can be produced at the core-mantle boundary by viscous, electromagnetic, topographic and gravitational coupling. Two candidate mechanisms under investigation for these decade variations are: (1) topographic torques due to dynamic pressure forces associated with core motions acting on undulations of the core-mantle boundary, and (2) torques of electromagnetic origin arising through Lorentz forces in the weakly-conducting lower mantle which could be significant if the unknown electrical conductivity of the lower mantle were sufficiently high. Estimates of topographic torques can be made from core motion deduced from geomagnetic secular variation in combination with core-mantle boundary topography deduced either directly from seismic tomography, or from dynamic models of the lower mantle based on tomographic and long-wavelength gravity anomaly data. Geodetic torque estimates inferred from the LOD provide a means of checking results from seismology and geomagnetism and imposing constraints on the models used.

3.5 Precession and Nutation

The external torques applied to the Earth by other bodies in the solar system (mainly the Sun and the Moon) cause a change in the direction of the Earth's rotation axis, its figure (or "body") axis, and its angular momentum axis. These motions are loosely referred to as precession and nutation, with precession being the secular-like part of the motion (period = 23,500 years) and nutation the more rapidly varying part. The response of the Earth to these externally applied torques is approximately that of a rigid body. However, there are observable effects that arise because the Earth is deformable, with a solid-inner core, fluid-outer core, anelastic mantle, fluid oceans, and an atmosphere. It is these effects of the Earth's deformability that make nutations geophysically interesting.

Currently, nutation series are computed assuming that the individual periodic components of the nutations can be linearly superimposed, and thus that the complete motion of the body axis with respect to inertial space can be obtained from the sum of all of the periodic nutations, precession, and the long-period motions due to polar motion. The sum of individual nutations of different periods form a nutation series. The IAU 1980 nutation series forms the basic series with which observations of the nutations are compared. Modern space geodetic techniques have already disclosed errors in this series which are related to the incompleteness of the geophysical models on which the theories are based. The most notable of these is an error in the retrograde annual nutation of about 2 mas amplitude. This correction has been interpreted as being due to the flattening of the core-mantle boundary (CMB) deviating from its hydrostatic equilibrium value by about 5%. A similar discrepancy between theory and observations has been recently observed in tidal gravity data, with results which are consistent with this increased flattening of 5%. This flattening result is of similar magnitude with the results inferred from studies of decade fluctuations in the LOD, described above, and is proving to be a valuable constraint on core/mantle boundary maps, based on tomographic and other data.

3.6 Polar Motion

Polar motion consists mainly of nearly circular oscillations at periods of one year (the annual wobble) and about 433 days (the Chandler wobble), with amplitudes of about 100 and 200 milliarcseconds (mas), respectively, together with a long-term drift of a few milliarcseconds per year. In addition, astrometric data sets exhibit decade time-scale polar motion, of amplitude less than 50 mas, while analysis of geodetic data reveals rapid polar motion, with peak-to-peak variations of approximately 2 to 20 mas, fluctuating on times scales between two weeks and several months. Comparisons with meteorological data suggest that these latter motions are at least partially driven by surface air pressure changes, as modified by the response of sea level to atmospheric loading. The annual wobble is due to the integrated effects of seasonal variations in mass distribution and the motion of air and water and thus provides an important global measure of seasonal variability on the Earth. The source of the Chandler wobble is uncertain and is under active research; candidates with various degrees of plausibility are the atmosphere and ocean, movements of ground water, seismic deformation and hypothetical torques from the core. Continual and improved monitoring of polar motion combined with improved models of air pressure and ground water may resolve the degree to which the atmosphere drives polar motion. The changing distribution of water in the ground and oceans and on the surface is likely to be important at periods of a year and longer. On time scales of hundreds to thousands of years, water storage variations in the polar ice caps and the associated loading deformation of the solid Earth is a dominant influence on polar motion. Although one must account for other secular variations in these calculations, much of the observed secular drift of the pole in this century can be explained by redistributions of water and ice together with the post-glacial rebound following the last Pleistocene deglaciation around 20,000 years ago. Contributions from plate motions, seismic deformation and present day melting of glaciers are also present; the study of these long-period polar motions is hampered by systematic errors in the optical astrometric data which must be relied on prior to 1976.

3.7 Tides, Temporal Variations of the Geopotential and Related Problems

Because the degree two spherical harmonics mass redistribution causes Earth rotation variations, it is sensible to examine time variations in other spherical harmonic constituents of the gravity fields in order to understand the physical processes which produce the redistribution. Comparison of LAGEOS-I orbit node residuals with accurate Earth rotation measurements from other techniques can be used to isolate changes in rotation caused by mass redistributions which affect the Earth's oblateness or the J_2 gravitational coefficient. The analysis reveals three significant nodal residual signatures in LAGEOS' orbit: an acceleration, together with annual, and semiannual periods. These signatures reflect temporal variations in the gravitational harmonic J_2 which measures the oblateness of the Earth and, hence, the polar moment of inertia. The seasonal terms are thought to be caused by a combination of ground water and air pressure changes and are equivalent to a 2 ms amplitude Earth rotation rate signature. The secular acceleration of the node implies a rate of change of J_2 ($\dot{J}_2$) which is consistent with historical observations of the nontidal acceleration of the Earth's rotation and models of the viscous rebound of the solid Earth determined from the decrease in load due to the last deglaciation. The determination of $\dot{J}_2$ is a significant milestone in that it is the first clear-cut demonstration of a secular change in the Earth's gravitational field. The long-term change is equivalent to a rate of change of J_2 of between -2 and -3 x 10^{-11} per year, and implies that the average mantle viscosity is about 3 x 10^{22} poise.

Perturbations in satellite orbits can also be used to infer tide heights (combined ocean and solid-Earth and Meteorological tides). Such perturbations depend on the tides' world-wide characteristics, and thus provide a global view of tides never before possible. Recently a landmark in tidal studies was achieved by the simultaneous determination (using a number of satellites) of 616 spherical harmonic components of 32 major and minor ocean tides. Finally, the use of satellite altimetry to map ocean tides has already begun, and shows much promise for eventually yielding high-resolution global tide heights, at least for the major tides.

4. OBJECTIVES FOR THE NEXT DECADE

4.1 Introduction

Earth rotation studies encompass precession, nutation, polar motion, Universal Time, and length-of-day. The scientific objectives of these studies are as follows:

> Observe and understand interactions of air and water (oceans, groundwater, and ice) with the rotational dynamics of the Earth, and their contributions to the excitation of Earth rotation variations, over time scales of hours to centuries;
>
> Observe and understand the effects of the Earth's crust and mantle on the dynamics and excitation of Earth rotation variations over time scales of hours to centuries;
>
> Observe and understand the effects of the Earth's core on the rotational dynamics of the Earth and excitation of Earth rotation variations over time scales of a year and longer;
> Establish, refine, and maintain terrestrial and celestial reference frames.

Careful reference frame definition, refinement, and maintenance are of great importance in cartography and space navigation, and are essential to the six scientific objectives of the Solid Earth Sciences Program. For example, the enhancement and realization of reference frame are of key importance in the proposed FLINN Network. In addition, observation and analysis of high-precision Earth rotation variations will contribute to each of these six as follows:

1. Earth rotation observations provide a unique way to study physical properties of and motions within the inaccessible core and to constrain magnitudes of viscous, magnetic and pressure forces acting at the core-mantle boundary.

2. Earth rotation observations provide the basis for an absolute reference frame for the description of plate motion and associated mantle convection.

3. Earth rotation variations arising from tectonic activity constrain the rheology of the lithosphere, and secular rotational variations may provide global constraints on other sources of mass redistribution such as sedimentation and erosion.

4. High-precision Earth rotation observations will provide integral measures of deformation, and its time history, associated with earthquakes and tectonic processes.

5. Secular Earth rotation variations constrain the history of the glacial ice masses over the Pleistocene.

6. Earth rotation observations provide integral measures of changes over the globe in the distribution and motion of air and water due to both natural and man-made causes. These observations also provide integral measures over the globe of the forces between the Earth and its fluid envelope.

4.2 Reference Frames Requirements

Improvements in system performance and the coupled measurements will drive reference frame requirements. The improvements in system performance required to meet our goals must be regularly monitored to avoid systematic errors that could be misinterpreted as Earth rotation signal. Such an assessment should be accomplished by direct comparison and colocation of techniques, which has the additional benefit of contributing to monitoring the reference frame, including the stability of the center of mass. Local ground surveys are needed at colocation sites. Earth rotation results can be directly compared between techniques to determine systematic differences in those systems. It is expected that GPS will have an increasingly important role in the reference frame aspects, especially in determining ties between the systems. As the GPS system matures, it will be necessary for GPS to define its own reference frame, including the determination of the center of mass. The center of mass origin defined by the space geodetic techniques has applications to areas which need an absolute determination of position, such as monitoring global sea level changes with the use of tide gauges.

In addition, improved ephemeris-radio frame ties can be accomplished by VLBI observations of pulsars, additional VLA observations of the outer planets and satellites, future differential VLBI experiments (such as that with orbiting spacecraft around Jupiter and Saturn), or space VLBI. Observations of LAGEOS and LAGEOS type spacecraft, illuminated by radar, would also greatly help to tie the SLR and VLBI reference frame. The millisecond pulsar PSR1937+214, having a period of 1.6 msec, has exceptionally low timing noise. Its position in the ephemeris frame can be measured to ~ 1 mas. This will allow a radio-planetary frame tie limited only by the accuracy of an interferometric position measurement. Roughly, a factor of five improvement (down to the 5-10 mas level) is expected here with the full implementation of VLBI observations.

Transforming between terrestrial and celestial coordinates requires knowledge of precession, nutation, as well as polar motion and UT1. LLR and VLBI detect significant corrections to the precession constant and nutation. The direction of the precession, or equivalently the location of the pole about which the precession takes place, is specified by the obliquity and the dynamical equinox. Both are determined by LLR.

4.3 Variation in Length-of-Day

The NASA EOS concept of an interdisciplinary mission is ideal for the type of investigations discussed here. The resultant data would allow for a better understanding of the total Earth system. The scientific problems highlighted here are not only of intrinsic interest for understanding variations in Earth rotation, but they also address important areas of research in each of the disciplines involved. For example, more extensive atmospheric and oceanic data will lead to a better knowledge of the dynamics and physics of the atmosphere and of the coupled atmosphere-oceanic system. Measurements of interest include improved determination of atmospheric pressure, stratospheric and tropospheric winds and oceanic circulation. Further, these data, coupled to highly accurate geodetic measurements of the Earth rotation vector, would permit new insights into the coupling mechanisms between the solid Earth, oceans and the atmosphere.

Thus far, most investigations relating LOD variations to changes in AAM have addressed the degree to which a balance is satisfied between these two quantities without regard to the torques responsible (computing torques is a difficult task with the data currently available). Studies aimed at achieving an improved understanding of the coupling mechanisms that link the solid Earth, atmosphere and oceans will be intimately tied to improving climate models. Better rotation data might lead to further identification of features in the atmospheric circulation that are poorly understood. To take full advantage of an improvement in the rotation accuracy, though, the accuracy of the meteorological data needs to be improved independently. The present uncertainties in the meteorological data are probably the same order or larger than the oceanic contributions to subseasonal LOD variations. Better knowledge of the atmospheric contribution would enable the use of rotation results to help assess global oceanographic models and altimeter-derived currents. In addition, improved determinations of the water cycle (that within the atmosphere, ground-water and oceans) are required to assess its effect on Earth rotation rate and polar motion, an area to which EOS and GEWEX (Global Energy and Water Cycle Experiment) can make a useful contribution. Coordinated, intensive, interdisciplinary measurement campaigns involving geodetic, meteorological and oceanographic data should be organized in conjunction with WOCE, TOPEX, and other relevant international programs; the resultant data sets would provide new insights into the coupled solid-Earth /atmosphere /ocean/hydrosphere system. For example, subtraction of atmospheric effects with more accurate data sets may allow oceanic and seismic contributions to be isolated. In addition, the benefits of high-frequency Earth-rotation measurements will extend to seismology (source phenomena and possible earthquake prediction) and studies of mantle anelasticity (by solving for the tidal LOD fluctuations). The largest LOD tidal fluctuations are produced by the fortnightly, monthly, semi-annual, and annual tides. The amplitudes are sensitive to mantle anelasticity, which is not currently well constrained in this frequency range. The fortnightly and monthly terms are potentially the most useful, because the LOD signal from the atmosphere and oceans is much smaller than at the seasonal periods.

On interannual time scales, continued studies of global or regional phenomena and indices, such as the El Niño/Southern Oscillation and the quasi-biennial oscillation, will lead to further advances. Here, the possibility exists that the ocean may contribute significantly to the momentum budget. In some respects, it is remarkable that a discernable role for the oceans in contributing to non-tidal LOD changes on any time scale has yet to be found, given that large amounts of momentum are likely being exchanged through frictional stresses between the atmosphere and ocean. It is conceivable that the ocean is simply transferring momentum between the atmosphere and solid Earth without acquiring any net momentum itself, but present measurements are inadequate to demonstrate the expected connection and elucidate the details. The oceans also affect the tidal response of the Earth through the rich spectrum of oceanic tides. From measurements of tidal changes in LOD we can hope to assess ocean tide models, constrain mantle anelasticity as a function of frequency, and possibly learn about the frequency dependence of core-mantle coupling. Quantifying the sources of energy dissipation due to tidal friction that cause a secular increase in LOD is critical for understanding the anelasticity of the Earth as well as the evolution of the Earth-Moon system. The loading of the solid Earth by the oceanic tides causes displacements that affect all geodetic measurements; their exact nature depends on the heterogeneous elastic properties and structure of the solid Earth over the range of tidal frequencies, as well as on global ocean tide characteristics. All these require better global models of oceanic tides than are presently available.

Secular variations in the rotation rate can be caused by tidal friction, post-glacial rebound, the melting of ice in the polar caps and continental glaciers, other secular changes in the surficial water budget (such as an increase in atmospheric moisture accompanying global warming), tectonic activity, mantle convection and core evolution. The effect of melting ice could conceivably be as large as 4 x 10^{-3} msec/year, depending on the rate of melting or accumulation from the different ice sheets. This number assumes that one-half of the observed global rise in sea level comes from the melting ice caps. However, it may be that the polar caps have ice budgets that are close to being in balance and that the observed non-steric sea level rise is due to mountain glaciers. In this case, the effect on the rotation rate would be about an order of magnitude smaller.

How could improved LOD observations help on these longer time scales? The most likely way of discovering what is occurring is to search for time-dependent correlations between the rotation observations and independent data sets such as temporal gravity results, magnetic observations, and meteorological and oceanographic variables. The answer lies in improving both these complementary data sets as well as those for Earth rotation. The goal should be to have decade-scale variability accurate to a few parts in 10^{11} for m_3. One advantage would be that the probability would increase of finding correlations with the important secondary effects, such as with those variables that reflect global warming.

4.4 Precession and Nutations

Since the adoption of the IAU 1980 nutation series, two sets of corrections based on theoretical considerations have been suggested. First, corrections due to the effects of ocean tides that are as large as 1.1 mas for the 18.6 year principal nutation, and 0.6 mas for the semi-annual nutation. Second, corrections for the effects of anelasticity of the mantle have been proposed. In addition, VLBI observations of the nutations have disclosed corrections to the retrograde annual nutation, prograde semi-annual, prograde 13.7 day, and the long-period nutations (the combination of the 18.6 year, 9.3 year, and the precession constant). These latter long period corrections cannot yet be separated accurately because of the short (7.5 year) span of Mark III, dual-frequency band VLBI data. Lunar Laser Ranging data, now spanning a twenty-year period with range accuracies varying from 25-30 cm in the early seventies to 2-3 cm currently, are useful for determining of these long period terms. A combination of LLR and VLBI is beneficial.

Overall, we see that the agreement between the IAU 1980 nutation series and the VLBI results is very good considering that the individual terms of the IAU series are rounded to 0.1 mas. Of the 32 corrections to the IAU series that were estimated, 11 corrections exceed 0.1 mas, and only seven corrections exceed 0.15 mas. For all but one of these seven corrections, corrections to the IAU series expected are based on the extension of the geophysical models used to derive this series. However, those theoretical corrections do not agree with the observed corrections. The one observed correction to the IAU series for which no geophysical model has been proposed that would predict a large correction is the 13.66 day prograde term. For this term the VLBI derived correction is -0.34 mas. Such a correction could arise if the changes in the principal moments of inertia of the mantle due either to tilting the mantle's rotation axis or to an external potential, are not corrected in the current nutation models. However, it is not clear that this relationship could be incorrect given the direct effect of such a parameter on the k_2 Love number. Instead, the effect may enter through an effect of the ocean's response.

One other correction that is anomalous by its absence is the freely excited core nutation. This free mode, which is analogous to the Chandler wobble, has a free period of about one day as seen from an Earth-fixed frame. The current bound of its amplitude placed by VLBI data is <0.4 mas. The question naturally arises as to why this mode is not excited to the expected level. From the solution to the forced nutation problem, estimates of the eigenfrequency of this mode and a lower bound on its damping time have been tightly constrained, and thus we must conclude that either the theory of the excitation of this mode is currently not correct, or that there is little power in the diurnal band which could excite this mode. Observations of the freely excited mode might also give insight regarding the damping and excitation processes. The excitation may be particularly interesting as it may give us information concerning stochastic processes in the core at diurnal periods.

Even now there are questions about the structure of the Earth which need to be answered to obtain agreement between the observed and theoretical nutations. The constraints which will be placed on the Earth models should become even stronger as more VLBI and LLR data are obtained. In the next decade, accurate estimates of the precession constant, with uncertainties <0.001"/century, about two orders of magnitude smaller than current uncertainties, and the 18.6 year nutations (uncertainty <0.1 mas) should be obtained when there is a sufficient duration of VLBI and LLR data to allow these long-period terms to be estimated separately. Based on observational evidence and the expected effects of changes in the flattening of the core-mantle boundary, ocean tides, and the anelasticity of the mantle, we know that corrections of the order of 1-2 mas for the 18.6 year nutation and 0.1-0.3"/century for the precession constant are needed for these terms.

In addition to space geodetic data, other ancillary data will be needed in the future to fully exploit the advantages of using nutation to study the dynamic response of the Earth to externally applied torques. Already it is clear that the effects of ocean tides are not negligible, and in the future we will need to know their contribution to better than 0.01 mas (about 2% of the effect on the semiannual nutation). Also, models for the dynamic effects of currents in the ocean will be needed. The long-term stability of the VLBI and LLR reference frames also needs to be established.

The analysis of nutation will yield information about the anelasticity of the mantle, dissipative coupling of the fluid core to the mantle, coupling of the solid-inner core to the fluid-outer core and the mantle, the principal moments of inertia of the Earth, and the excitation of the Earth with periods near one day (particularly those from the atmospheric and oceanic loading). Improved nutation results could also provide useful constraints on mantle anelasticity at diurnal periods (where information is sorely lacking). A factor of 5 or so improvement in the nutation results would yield accuracies that are better than the differences between anelastic models. The major limitation, even now, however, is probably due to uncertainties from other effects -- principally from the ocean corrections. Hence coupled improvements as discussed above are required. In general, the presence of the fluid-outer core, and possibly the solid-inner core, have major effects on the nutation, and thus nutation studies, may provide sensitive probes of the internal dynamics and structure of these parts of the Earth. Improvement in the nutation theory could yield some valuable information about the shape of the inner core/outer core boundary for the seismic evidence is currently meager. Although researchers have investigated individual spherical harmonics, no attempt has been made to map the boundary, and it is very difficult to separate undulations of the boundary from horizontal variations in composition in the seismic inversion models. An order of magnitude improvement in the nutations could give some interesting results through observations of either the forced nutations or, less likely, of the freely-excited inner core nutation. It does seem reasonable at this time to expect that nutation series coefficients with uncertainties of about 10 marcsec will be determined within the next decade by VLBI. The complexity of the Earth models that will result will increase our knowledge of the Earth's interior and its dynamics.

4.5 Polar Motion and Temporal Variations of the Geopotential

Polar motion studies suggest a number of unsolved problems that will require new measurements and study in the next decade. These problems include:

Contribution of air and water to polar motion excitation

Advances in geodetic measurement techniques during the past decade have led to the first unambiguous detection of polar motions on time scales between about two weeks and several months, which are driven at least partially by surface air pressure changes. A considerable fraction of intraseasonal atmospheric changes, however, reside at periods shorter than two weeks, about the current resolution limit of the polar motion excitation as deduced from polar motion data. Hence, it seems likely that very rapid polar motions on time scales of less than two weeks exist, so that high-accuracy and high-frequency measurements need to be obtained to detect them and to identify their excitation sources.

Annual polar motion is due to the integrated effects of seasonal variations in mass distribution and motion of air and water and thus provides a valuable global measure of seasonal variability on the Earth. Although major contributors to annual polar motion have been identified, there remains a significant discrepancy between the observed annual wobble and that which is predicted from meteorological observations. This discrepancy implies a lack of understanding of seasonal variability in the mass distribution on the Earth. Among the interesting problems that need to be addressed in understanding the annual wobble are the dynamic behavior of the oceans in response to surface forcing by barometric pressure and winds at seasonal time scales, and the seasonal variation in water storage on the continents. On time scales longer than a year, polar motion may also provide a uniquely global measure of climate variability as the Earth responds to long-term changes in ice volumes and inland water storage. The role of the atmosphere and oceans in the excitation of the 14-month Chandler wobble, and longer period polar motion needs to be quantitatively assessed so that the residual polar motion can be firmly attributed to non-meteorological/oceanographic sources.

Non-atmospheric sources of polar motion.

Research performed thus far seems to indicate that the atmosphere typically accounts for less than half of the variance in polar motions, whether they be at the Chandler, annual or rapid time scales. Thus there may be a source of excitation besides air and water. Mass displacements associated with earthquakes and slower tectonic events (co-seismic, aseismic, or post-seismic) may directly excite the Chandler wobble at the currently observable level; the current accuracy of measurements of pole position coupled with corrections for atmospheric effects should allow a major earthquake (moment $\sim 10^{29}$ dyne-cm) to be seen. The co-seismic displacements from an extremely large earthquake (such as the 1960 Chilean earthquake) could excite the Chandler wobble to 20 masec. The excitation from a moderately large earthquake is typically orders of magnitude smaller. In addition to the displacement in the pole position, a secular change in the LAGEOS node rate would be seen.

More exciting, perhaps, is the possibility of observing the effects of slower, aseismic displacements; those associated with earthquakes may even be precursors, and, in any event, may produce displacements and strains unpredicted at present. It is unclear what the excitation from an aseismic slip might look like. However, less than millimeter-level accuracy and high temporal resolution are needed to resolve the effects of all but the largest individual events and to see if the observed effect of an earthquake is adequately described by the elastic theory. The problem is that it is difficult to distinguish the solid Earth signal from meteorological effects and to be confident of time-dependent correlations between the polar motion and earthquake in the presence of meteorological effects. A better understanding of the meteorological forces that drive polar motion variations are required to separate the meteorological signal from that of the solid Earth response to earthquakes and other tectonic phenomena. Post-seismic anelastic relaxation would also contribute to polar motion; if observed, this would illuminate crust and lithosphere rheology and the nature of strain propagation following earthquakes.

Longer term mass redistributions due to post-glacial rebound, current ice melting and other phenomena also contribute to present long period secular polar motion and to temporal changes in the components of the gravity field. These are effectively monitored by the analysis of the LAGEOS (and LAGEOS-like satellite) nodal residuals. Mass redistribution might one day be "imaged" by combining SLR and Earth rotation change since each type of measurement is sensitive to different spherical harmonics. Improvements in modeling and measuring post-glacial rebound will lead to a better determination of secular polar motion and to the separation of this effect from current air and water mass redistributions, including melting of ice sheets and glaciers. The effects of melting ice (polar ice caps and continental glaciers) could possibly be as great as 1-2 mas/yr in polar motion, if one-half the observed global rise in sea level comes from the ice caps. As noted earlier, it may be that the polar ice caps have ice budgets that are nearly in balance, and that a large portion of the sea level rise is caused by mountain glaciers. In this case, the effects on the polar motion would be ~0.5 masec/yr. Removal of post-glacial rebound from the secular trend will also allow the cumulative effect of earthquakes and related phenomena on polar motion to be constrained.

The explanation for the decade-scale variability in polar motion requires further study. One major source could be the exchange of angular momentum between the core and mantle; in fact, present data would limit the amount of topographic core-mantle coupling. Mantle deformation caused by core pressure change and the effects of long-period variability of the global ice and water budget, including long-period behavior in the ocean, could be a factor as well. As with decade variations in LOD, we recommend improved polar motion series (accurate to a few tenths of a milliarcsecond) and improved coupled complementary data sets such as gravity, geomagnetic and oceanographic data. Long-term continuation of homogeneous series of polar motion measurements is essential for accurate determination of decade and secular polar motions, given the systematic error in the data available from before 1976.

From known amplitudes of semi-diurnal and diurnal ocean tides, we can expect the short-period tides to perturb polar motion periodically with typical amplitudes of 0.1 mas or larger. Thus, measurements of high-frequency polar motion may allow discrimination between different theoretical tide models, shedding light on ocean dynamics at daily time scales. The tidal signals are dominated by the signals from semi-diurnal and diurnal solid-earth tides; careful analysis of the polar motion data may yield information on high-frequency mantle anelasticity. It should also be possible to pick out the amplifications caused by the fluid core free resonance, which is narrow-band and nearly diurnal; such detection would provide a supplemental view of core properties to that recently obtained from nutation studies.

The "inverted barometer" and role of the oceans.

Complicating the analyses of polar motion excitation are uncertainties about the manner in which the ocean responds to forcing by the atmosphere above it and the degree to which this response is then communicated to the solid Earth. Data are currently inadequate to determine the detailed dependence of the transfer function between sea level, atmospheric pressure, and wind stress forcing. Theoretical delineation of this transfer function, based on realistic ocean modeling, is also required.

4.6 Tides and Tidal Dissipation - An Example of a Multitechnique Approach

Dissipation of rotational kinetic energy in the tides have had the largest single effect on the LOD over the history of the Earth. Thus improved determinations are important and provides an excellent example of the complementarity of various techniques and how different systems and techniques can be used together in attacking a problem. LLR determines the recession of the Moon which is primarily due to tidal dissipation in shallow seas. The present estimate of the rate of change of lunar mean orbital angular velocity is -24.9 ± 1.0 arcseconds/century^2, equivalent to 3.7 ± 0.2 cm/year in mean distance. The uncertainty of this measurement will be reduced to less than 0.5 arcseconds/century^2 by 1990.

LAGEOS' orbit is also perturbed by the Earth's dynamic tidal gravity field, sensing the amplitudes of individual tidal constituents. Measurements of a variety of tidal components using LAGEOS and other satellite data can be used to predict independently the lunar recession rate. A satellite prediction for lunar acceleration from measured tides is -25.3 ± 0.6 arcseconds/century^2. Comparing the LAGEOS data with the lunar measurement will indicate if there is a significant non-ocean-tide component of lunar acceleration. These data can then be compared with estimates of lunar dissipation caused by solid friction and core-mantle friction, consistent with the observed lunar libration (the Moon's rotation) signature. The solid friction mechanism predicts a small but measurable 0.4 arcsecond/century^2 contribution to lunar acceleration, while that from core friction is several times smaller.

Other combinations of data could reveal the fraction of tidal dissipation due to solid friction in the Earth. The vertical motion represented by the principal tidal constituents can now be estimated with about 1% uncertainty by the IRIS network. A modest improvement in this system together with more data may reveal the phase lag caused by solid friction, if the contribution from ocean tides can be accurately removed using tidal models. The planned TOPEX mission, among other things, will obtain topographic maps of the major tidal constituents. The solid Earth elastic model constructed from seismic data indicates a 1% decrease in mantle rigidity in the 1 to 3000 second period band. This effect is attributed to anelastic dispersion. Some models for this dispersion predict that there may be an additional 1% increase at diurnal frequencies and it could be as large as 10% for the 18.6 year zonal tide. Thus, the complementary tidal data from each of these systems will eventually determine the anelastic dispersion parameters of the solid Earth.

5. REQUIREMENTS

Requirement 1. Determine the rotation vector and its variations with the highest possible accuracy (at least 0.1 milliarcsecond) and with a sampling frequency of at least four cycles per day.

Improve analysis and modelling capabilities to a level commensurate with the improved spatial and temporal resolutions.

Collect improved ancillary data from geophysical, oceanographic, and atmospheric sources to enhance the interpretation and understanding of fundamental processes.

Pursue alternative synergistic and innovative approaches for Earth rotation measurements, such as the emerging global network of GPS stations and other new techniques.

Rationale. Changes in the Earth rotation vector are a consequence of changes of the inertia tensor of the solid Earth and Earth's response to both periodic and irregular applied torques. The recommended measurements will observe the periodic torques applied to the Earth by external planetary bodies, the resonances in Earth rotation due to the fluid-outer and solid-inner cores, and additional aperiodic variations to study the dynamic response of the solid Earth to external forces and forces applied by its fluid parts (atmosphere, oceans, and fluid-outer core). None of the currently available AAM series has the temporal resolution needed to provide the estimates at periods less than diurnal. Recent improvements in global atmosphere modeling suggest that the global weather forecast models should be able to provide the information in the near future. Efforts should be taken to obtain AAM information with smaller sampling times as it becomes available.

The high-frequency data and complementary analyses can be expected to lead to delineation of short-period tidal, atmosphere, and "coseismic" effects on wobble and LOD. These in turn will improve our understanding of broad-band wobble excitation processes and seismic source behavior, fluid-core resonance characteristics, and mechanisms of ocean/atmosphere coupling to the solid Earth. Both the accuracy and frequency of geodetic measurements of variation and polar motion need to be improved. Discrepancies between LOD variations and AAM at very high frequencies are currently smaller than the errors associated with each of these quantities individually, which are typically somewhat less than 0.1 ms (1.5 mas). From the examination of AAM data (available on a sub-daily basis), we can deduce that the sub-daily variations in LOD could be 0.05 milliseconds (or 0.75 milliarcseconds) in magnitude or less. To study these signals, the measurement needs to have smaller uncertainties; the accuracy should be on the order of 0.007 milliseconds or 0.1 milliarcseconds. Semi-diurnal variations exist; hence a measurement program of several cycles per day (at least four per day) is needed. At this level, the effect of earthquake excitation and water motion could be investigated more fully.

The coupling, transfer, and storage of angular momentum involving the fluid and solid parts of the Earth would be determined with the aid of complementary geophysical, atmospheric and oceanographic data. Also, it is clear that as the accuracy of observations of the rotation of Earth improves, the distinction between nutations and short-period polar motion will become less clear. In the future, we will need to treat Earth rotation as a process having a continuous spectrum with power at all frequencies. Superimposed on this continuous spectrum will be the spectral lines at frequencies near $\approx$1 cpd associated with forced nutation. In particular, the contribution of the continuous spectrum will need to be removed from nutation results before these latter can be fully exploited for studying the response of the Earth.

The high accuracy of the data (boosted even more for the daily to weekly data by averaging over the sub-daily values) will lead to improvements in our understanding of aseismic and other tectonic processes, and oceanic and atmospheric variability -- through their effects on wobble and LOD -- on time scales ranging from sub-daily through interannual to decadal. The roles of ocean dynamics versus mantle anelasticity in modifying the long-period tidal variations in LOD and -- for the first time -- wobble should become clear, while the assumed minor role of the ocean in exciting non-tidal LOD should at last be detectable. Eventually, on even longer time scales, phenomena thought to excite secular polar motion and secular changes in rotational speed, e.g., viscous mantle rebound, redistribution of surficial mass (water, ice, and lithospheric), core couples, and tidal friction, will become better understood as the rotational features are measured with greater detail. The response of the solid Earth depends on its internal rheological properties which are not amenable to direct study. These measurements would also support the maintenance of a terrestrial coordinate system in which millimeter point positions could be expressed.

Requirement 2. To monitor and refine the celestial and terrestrial reference frames needed for Earth rotation and crustal motion studies, as well as space exploration, the following actions are required:

> Extend the quasar source catalogues to include additional suitable sources primarily in the Southern Hemisphere and along the galactic equator.
>
> Expand the quantity, quality, and global distribution of LLR observations to allow the continuing and accurate determination of the dynamical reference frames, the Lunar/Planetary Ephemerides.

Enhance and monitor the origin, orientation, and scale of the terrestrial reference frames and their ties at the 1 millimeter level, using techniques such as SLR.

Tie the above reference frames together and to those defined by artificial satellites using techniques such as colocation or differential VLBI.

In coordination with other US agencies and other nations, establish a minimum of three space-geodetic observatories per major tectonic plate, at sites distant from the plate boundaries, with regular measurement programs to monitor intraplate stability.

Establish a program of regular auxiliary measurements, such as gravity, at key globally distributed sites.

Rationale. A common requirement for all geodetic and geodynamic investigations is the necessity of well defined conventional inertial and terrestrial reference frames to which all relevant observations can be referenced and in which theories or models for the dynamic behavior of the Earth can be formulated. This requirement is particularly important to enable separation of station motions caused by global tectonics and local crustal deformations from the rotational characteristics of the Earth. The requirement is vital in the intercomparison and combination of results from the various space techniques.

Requirement 3. Improved observations of crustal motion and mass redistribution on the Earth. To permit quantitative comparisons between Earth rotation variations and crustal deformation, millimeter-level geodetic positioning is required at selected locations, over distances of 100 km or larger, on time scales of days (for co-seismic deformation) to decades (for post-glacial rebound).

Quantitative comparisons between changes in Earth rotation and oceanic mass will require determinations of global sea level.

Such quantitative studies will also require suitable monitoring of temporal variations in the gravity field.

Rationale. Taking measurements at a variety of temporal resolutions allows a number of topics to be addressed:

High-frequency measurements (such as diurnal, semidiurnal) would allow deformation and rotation fields due to the solid Earth, atmosphere and ocean tides to be studied. Nearly step-wise changes caused by crustal displacements associated with major earthquakes would be observed.

Seasonal temporal resolution would permit the mass displacement from the hydrosphere and the atmosphere to be measured and analyzed.

Long-time observations would determine quasi-secular changes driven by post-glacial rebound and present-day glacial melting.

Deformation of the Earth's surface and temporal changes in Earth's gravity field should be simultaneously monitored using space geodetic techniques with very high spatial and moderate time resolution. It is expected that these will elucidate both the radial and lateral elastic as well as anelastic structure of the Earth's interior. To distinguish among the various proposed sources of secular polar motion, thus allowing more reliable determination of mantle viscosity structure and inferences of alternative mantle rheology and facilitating the detection of global warming indicators, the gravity field and surface deformation should each be determined, at least four times per year. This should be complemented by regional deformation measurements. With this sampling rate, many of the sources of seasonal variation in the hydrosphere and atmosphere can be isolated, helping in the interpretation of semi-annual as well as annual signals in geodetic (satellite, rotational, and tidal) time series; this sampling rate also allows the seasonal periods to be better eliminated in the analysis for secular polar motion and secular changes in rotation rate.

Acknowledgment: The Panel benefited from input and discussions from many individuals including W. Carter, R. Hide, D. McCarthy, and J. G. Williams.